Application Note 5

# Currents & Open Circuit Voltages for Intrinsic Safety Considerations

## Introduction

Electrochemical sensors are generally devices which only produce very small voltages and currents and are not able to store large quantities of energy. In certain circumstances, therefore, it may be possible to consider them as simple apparatus as defined in BS 5501. Paragraph 1.3 of the 'general requirements' states that:-

"*Devices in which, according to the manufacturer's specifications, none of the values 1.2V, 0.1A, 20µJ, or 25mW is exceeded need not be certified or marked.*"

To consider whether the sensors can be covered by this statement we need to look at:-

A) The electrical characteristics of the sensors in normal operation

B) The possible fault conditions and what they might produce.

**Note:** Previously much attention has been focused on the potential short circuit currents which might be produced if a sensor is open circuit, exposed for a period to a high level of an electrochemically active gas and subsequently shorted out. It is worth noting that this condition requires two countable faults to occur with the exception of the condition of replacing the sensor in a hazardous area.

## Oxygen Sensors

### A) Currents and voltages generated under normal operation at 20°C.

1) Current outputs

Current outputs in dry, ambient air are:

| | | | |
|---|---|---|---|
| **C/N** | : 1.3mA maximum | **C/Y** | : 1.0mA maximum |
| **C/2** | : 0.6mA maximum | **C2N** | : 0.6mA maximum |
| **C/2PN** | : 0.5mA maximum | **2FO** | : 0.5mA maximum |
| **4C** | : 0.4mA maximum | **6C** | : 0.4mA maximum |

All the above sensors are non-linear and shows increasing sensitivity at oxygen concentrations above normal ambient air levels of 21%. Maximum currents of 10mA are observed in pure oxygen.

2) Open circuit voltages

In tests carried out at City Technology, measurements made of open circuit voltages over the range 10-100% $O_2$ were less than 0.8 volts for all oxygen sensors. Therefore there is no known way that the open circuit voltage can exceed 0.9 volts.

### B) Max. current on short circuit from an open circuit condition.

Peak current values of 200mA maximum were recorded on oxygen sensors over the concentration range 10 to 100% $O_2$. These peaks decay rapidly, within a few seconds, to the normal operating currents as oxygen within the cell is consumed and further ingress is controlled by the capillary diffusion barrier.

Peak short circuit currents are primarily a function of the open circuit voltage generated and are similar for all oxygen sensor types. Variations might be expected on testing larger sample sizes, but it is unlikely that currents would ever reach significantly greater values than 200mA and a reasonably safe limit to quote would be = 500 mA.

### Summary on Oxygen Sensors.

Maximum current in normal operation (pure $O_2$) = 0.01 Amps.
Maximum open circuit voltage (10 to 100% $O_2$) = 0.9 Volts.
Maximum peak short circuit current (10 to 100% $O_2$) = 0.5 Amps.

## Toxic Sensors.

### A) Currents and voltages generated under normal operation at 20°C.

1) Current outputs

All sensor types are linear over the recommended operating range of gas concentration and the current generated is given by the equation:

| cell sensitivity | x | gas concentration | = | cell output |
|---|---|---|---|---|
| ($\mu$A/ppm) | | (ppm) | | ($\mu$A) |

How a sensor behaves when exposed to concentrations above its recommended range depends on whether it has two or three electrodes. In both cases, exposure to such high concentrations results in severe polarisation at the *counter* electrode.

**(a) Three-Electrode Sensors -** The *sensing* electrode is controlled, relative to an unpolarised *reference* electrode, by an external operational amplifier circuit. Unlike two-electrode sensors, the *sensing* electrode potential is independent of the *counter* electrode polarisation. Tests on these sensors have shown a linearly increasing output with gas concentration until the output current exceeds the saturation current of the controlling external amplifier. At this point no further current change is possible with increases in gas concentrations. The maximum current limitation of amplifiers commonly used with a three-electrode sensor control is unlikely to exceed 50mA.

2) Voltages generated

**a) Three electrode sensors** - In normal operation the cell potential will be the sum of the *sensing-reference* and *reference-counter* potentials. There are two cases to consider:

i) For zero bias sensors the *sensing-reference* potential will be zero (<10mV). The *counter* electrode potential, however, is free to float relative to the *reference* electrode and will polarise as it produces the required cell current. The degree of polarisation is dependent on time and concentration. However once a polarisation of 1.05V has occurred the *counter* electrode will begin to evolve hydrogen and no further polarisation can take place. This means the maximum theoretical cell voltage for an unbiased sensor is 1.05V.

ii) The above consideration of *reference-counter* potential applies equally to biased sensors, but the *sensing-reference* potential may be greater than zero. The current recommended bias settings are:

| | | | |
|---|---|---|---|
| **3ETO/7ETO:** | +300mV; | **3HL/7HL:** | +300mV |
| **3AM/7AM:** | +300mV; | **3NT/7NT:** | +300mV |

Therefore the maximum theoretical cell voltage for biased sensors is 1.35V. However in practice *counter* electrodes do not polarise as far as hydrogen evolution (e.g. at its maximum overload of 5000ppm NO, measurements made on a 3NF/F show a stable polarisation voltage of 800mV, giving a total cell voltage of 1.1V). It is therefore true to say that, in practice, even in biased operation cell voltages are normally less than 1.2V.

## B) Maximum values of open circuit voltages

The MAXIMUM POSSIBLE potential is given by the NERNST equations for the electrochemical reactions at the *sensing* and *reference* electrodes.

The *reference* electrode is essentially the oxygen electrode reaction:

$$O_2 + 4H^+ + 4e \rightarrow 2H_2O$$

This reaction is irreversible and the true Nernst potential is never observed, even on very active electrocatalysts such as platinum. Maximum observed potential for City Technology *reference* electrodes is about 1.05 volts on the Normal Hydrogen Electrode Scale (N.H.E.). In some sensors lower potential references are used and this is taken into account when deriving the figures on the following page.

The following maximum possible potentials of the various *sensing* electrode reactions are calculated against the observed *reference* oxygen potential. The figures assume the subject gas reactions achieve the NERNST potential:

| | |
|---|---|
| $CO + H_2O \rightarrow CO_2 + 2H^+ + 2e$ | 1.25 V |
| $SO_2 + H_2O \rightarrow SO_3 + 2H^+ + 2e$ | 0.75 V |
| $H_2S + 3H_2O \rightarrow SO_3 + 8H^+ + 8e$ | 0.76 V |
| $H_2 \rightarrow 2H^+ + 2e$ | 1.05 V |
| $Cl_2 + 2e \rightarrow 2Cl^-$ | 0.80 V |
| $NO + H_2O \rightarrow NO_2 + 2H^+ + 2e$ | 0.37 V |
| $NO_2 + 2H^+ + 2e \rightarrow NO + H_2O$ | 0.20 V |
| $12NH_3 + I_2 + 6H_2O \rightarrow 2IO_3^- + 12NH_4^+ + 10e^-$ | 0.60 V (see note) |
| $PH_3 + 4H_2O \rightarrow H_3PO_4 + 8H^+ + 8e^-$ | 0.20 V |

**Note:** Ammonia sensors employ a unique electrolyte. The $NH_3$ reaction mechanism in this electrolyte is different to the oxidation and reduction techniques used in other sensors. However the maximum possible potential is still calculable.

From these equations we see that the maximum open circuit voltage will be less than 1.2V in all cases except CO. The theoretical maximum for CO is 1.25V, which corresponds to 100% CO. At lower concentrations the voltage will be reduced by 60mV/decade (e.g. giving 1.19V @ 10% CO).

In practice, however, the above estimates of MAXIMUM POSSIBLE open circuit voltage are unlikely to be achieved for the following reasons:

(a) Many of the reactions, particularly that of CO, are irreversible, so the full NERNST potentials are never realised.

(b) The presence of oxygen at the *sensing* electrode creates a mixed potential which reduces the *sensing-reference* potential difference.

(c) In the open circuit condition, reactant gas can diffuse to the *reference* and *counter* electrodes causing an equalisation of potential differences (e.g. a 3H sensor introducing to 100% $H_2S$ in an experiment produced no measurable cell potential).

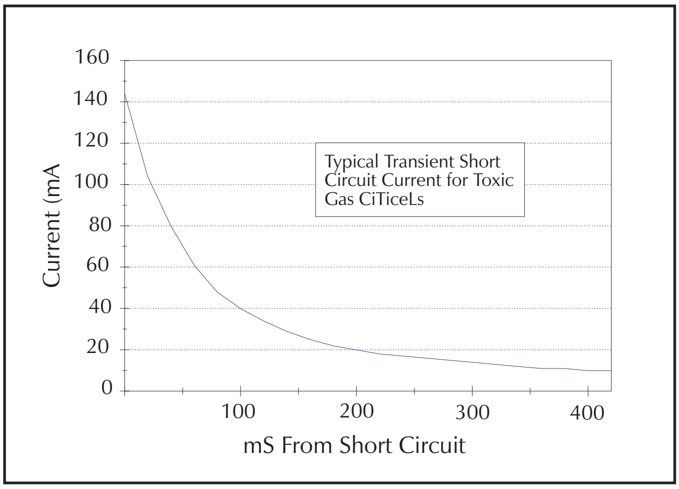
Measurements made at City Technology show that the above factors do in fact limit the open circuit voltages quite substantially, even with exposure to very high concentrations. For example, 0.75V was recorded on a CO sensor exposed to 20% CO and 0.36V was recorded on a $H_2S$ sensor in 900 ppm $H_2S$. Since these potentials vary according to the logarithm of the gas concentration, open circuit voltages will not vary greatly at higher concentrations.

In summary, although it is theoretically possible to generate more than 1.2V in an open circuit situation, in practice this is never observed.

## Max current on short circuit from an open circuit condition

As for oxygen sensors, peak short circuit currents will be a function of the open circuit potential developed during the open circuit. The maximum measured value in tests at City Technology, in 20% CO, was 0.47 amps from an open circuit potential of 0.75 volts. The maximum possible potential is 1.2 volts and therefore we can deduce that the MAXIMUM POSSIBLE short circuit current would be 1 amp.

**Figure AP5.1**
Short Circuit Currents




## Summary on Toxic Gas Sensors.

| |
|---|
| Maximum current possible in normal operation = 0.05 Amps. |
| Maximum cell voltage possible in normal operation = 1.2 Volts |
| Maximum open circuit voltage possible = 1.2 Volts. |
| Maximum peak short circuit current possible = 1 Amp. |